Final Technical Report for: 04HQGR0015

IMPROVING THE SEISMIC HAZARD MODEL FOR PUERTO RICO: A RELIABLE MICROEARTHQUAKE CATALOG THROUGH SEISMIC VELOCITY MODELING AND MICROEARTHQUAKE JOINT LOCATION

Dr. William R. McCann
10210 West 102nd Avenue
Westminster, Colorado 80021

Tel./fax (303)650-5484
Email: wrmccann@comcast.net

FINAL TECHNICAL REPORT FOR: 04HQGR0015

IMPROVING THE SEISMIC HAZARD MODEL FOR PUERTO RICO: A RELIABLE MICROEARTHQUAKE CATALOG THROUGH SEISMIC VELOCITY MODELING AND MICROEARTHQUAKE JOINT LOCATION

Dr. William R. McCann
10210 West 102nd Avenue
Westminster, Colorado 80021

Tel./fax (303)650-5484
Email: wrmccann@comcast.net

Abstract

Thousands of P-wave arrival times from hundreds of locally recorded earthquakes were used in the program *Velest* to develop two new seismic velocity models and stations delays for Puerto Rico and the Virgin Islands region in the northeastern Caribbean. In the area beneath Puerto Rico (PR) the crust is 30 kilometers thick, in agreement with gravity estimates made over 40 years ago. The preferred PR model has two layers over a half space. V_p is 6.45, and 7.13 km/sec in the crust and 8.01 km/sec in the upper mantle. Station delays suggest a difference in crustal/ thickness or average velocity for the region on either side of the Great Southern Puerto Rico Fault Zone. More than sixty quarry blasts were used to estimate the absolute and relative location errors using the PR model. In the region near Naranjito, NW Puerto Rico, artificial seismic sources are located near the surface, but with a to-the-west and slightly south location bias of 1-2 kilometers.

In the Virgin Islands, the more complicated tectonic environment and the lower number of events available for the inversion procedure makes the results less reliable. Nevertheless, it is clear that the upper mantle P-wave velocity is significantly lower than that beneath Puerto Rico. Data also suggest a crustal thickness of about 29 km. Artificial seismic sources in this region appear to have a 500 meter to-the-west bias in their locations.

Introduction

Using gravity and seismic refraction data, Officer et al. (1957, 1959) and Talwani et al., (1959) estimated the crustal thickness for the region around Puerto Rico and the Virgin Islands. They found the crust beneath Puerto Rico to be about 30 km thick and about 20 km thick beneath the Anegada Passage to the east. North of the islands, the crust of the Atlantic Ocean floor was found to be about 5 kilometers thick, and that beneath the Caribbean Sea significantly thicker. Since that time the collection of a wealth of new geophysical data, in particular locally recorded earthquakes, gives us a robust database with which to more precisely determine the crustal and subcrustal structure of the region.

In 1974, local seismic stations started monitoring earthquake activity in the U.S. Caribbean. The number of recording station rapidly grew to over 30 covering about 400km of the local seismic zone (Tarr and King, 1976; Murphy and McCann, 1979). A catalog of locally recorded earthquakes, accumulated over more than 25 years of recording, now contains about 20,000 events. Accurate location of these locally recorded events depends upon a seismic velocity model that reasonably represents the real crustal structure. To that end several investigators estimated the local crustal structure using a variety of seismological techniques (Asencio, 1980; Fischer and McCann, 1984; Huerfano and Bataille, 1994).

In this part of the Caribbean most earthquakes occur outside the relatively narrow band of islands comprising the eastern portion of the Greater Antilles, resulting in azimuthal gaps of 180° or more. This fact, coupled with complexities in the geologic, and tectonic framework of the region presents particular problems for the accurate location of seismic events. For example, many earthquakes are associated with one of two downgoing seismic zones of opposing dips that plunge beneath the island chain from the north and south. Dipping crustal units associated with these Wadati-Benioff Zones complicate the earthquake location process.

For the last several years, efforts to improve the catalog of events in the Puerto Rico Virgin Islands region have been underway. Data originally collected by two separate networks were combined into a unified catalog and digital waveforms collected in the 1980's rescued and put into a modern format (McCann, 2002). Some of this rescued data includes arrival times for multi-ton shots detonated in the marine area to the north of the network, a station to station marine refraction line, refraction lines and local earthquakes recorded at numerous OBS sites throughout the Virgin Islands region, and local construction blasts or quarry shots all useful to calibrate the local velocity structure. The long-term goal of these efforts is to create a catalog of well-located events, with well-determined magnitudes, so that the network catalog can be included in PSHA calculations.

Herein I report on results of efforts to develop 1-Dimensional P- and S-wave velocity models for the region of the Puerto Rico seismic network using the FORTRAN program *Velest* (Kissling, 1995). The successful developments of these models allow improved local earthquake locations, and enhance efforts to better understand the seismotectonics of the region and later permit the local catalog to be included in Probabilistic Seismic hazards analyses (Mueller at al, 2003a,b; LaForge and McCann, 2005). Arrival times from the artificial sources in the area have already provided valuable information concerning both relative and absolute errors in location of seismic events and will be useful in future efforts to develop a 3-D model for thee region.

General Geology and Neotectonics of the Northeastern Caribbean

Puerto Rico and the Virgin Islands lie on a long, narrow platform, a shallow, partially subearial submarine bank at the easternmost end of the Greater Antilles Island Chain (Figure 1). These islands were formed in the Cretaceous to the early Cenozoic as an island arc overlying a south or southeasterly-directed subduction zone consuming proto-Caribbean seafloor and are composed of intrusive and extrusive volcanics, and an overlying cap of carbonate and other sedimentary rocks (Jolly et al., 1998). Puerto Rico is composed of three principal provinces separated by the great northern and southern Puerto Rico fault zones. Major motion on these faults ceased by Eocene time. The northern and central domains are much more similar in composition, while the western one is distinctly dissimilar, containing serpentinized peridotites and other rocks representative of lithospheric upper mantle, suggesting and early development different than the rest of the island (Jolly et al., 1998). Sedimentary rocks of Tertiary age lie along the northern and southern coasts. The Virgin Islands are composed of a volcanic intrusives, extrusives and metamorphosed volcanoclastics (Donnelly, 1966; Rankin, 1997).

Puerto Rico and the Virgin Islands lie near the northeastern corner of the Caribbean Plate (Figure 1), to the north and east lays the westerly moving North American Plate. The Puerto Rico-Virgin Islands platform straddles and is cut by major tectonic and seismically active features that form the plate boundary zone between these major plates. The microplate is bounded by the traces of subduction zones along the Puerto Rico Trench (PRT) to the north, the Muertos Trough (MT) to the south (Sykes and Molnar, 1969; Byrne et al, 1985). Just to the southeast of Puerto Rico, a transtensional zone in the Anegada Trough (AT) cuts the Virgin Islands (Jany et al., 1987; Lithgow, et al., 1987). Finally, a wide zone of transtension in western Puerto Rico, Mona Passage and the eastern Dominican Republic bound the microplate to the west (McCann, 1998; Jansma et al., 2000; Mann et al., 2002). The first two features form margins of the major plates and the later two edges of microplates within the plate boundary zone (Byrne et al, 1985). The rate of movement between the major plates near Puerto Rico as measured by GPS, is about 19-20 mm/yr (DeMets et al, 2000). Rates of movement along secondary features representing microplate movements was estimated using historic and microearthquakes, and later measured using GPS to be about a factor of ten less (McCann, 1985; Jansma et al., 2000, Jansma and Matiolli, 2005).

The northeastern Caribbean is dominated by the slow (16mm/yr) subduction of the North American lithosphere (NA) beneath the microplates buffering motion between it and the leading edge of the Caribbean Plate (CA, Figure 1). Focal mechanisms of earthquakes on the plate interface indicate interplate slip in a direction of S70°W (Deng and Sykes, 1995). In the Lesser Antilles, this means slightly oblique subduction of NA along an easterly dipping interface. Subduction gradually increases in obliquity towards the segment of the margin near Puerto Rico and Virgin Islands. There, subduction is extremely oblique, with slip vectors of focal mechanisms nearly parallel to the strike of the trench axis even though the interface dips south. Intermediate depth events on an inclined seismic zone reach 125 km beneath the islands. Plate motion studies have shown that NA-CA slip directions have remained essentially unchanged for at least the last 5 Ma (Muller et al., 1999).

Along the southern margin of the PRVI microplate the Caribbean Plate obliquely subuducts at about 2½ mm/yr (Jansma and Matiolli, 2005). The trace of that subduction zone is the Los Muertos Trough that extends from central Hispaniola in the west to south of the

Virgin Island in the East. An accretionary prism is clearly defined from about eastern Puerto Rico to the termination of the trough in the west. (Ladd and Watkins, 1977; 1978; Matthews and Holcombe, 1976; Silver, 1972; Garrison et al., 1972). The Caribbean lithosphere has a complex and still controversial history (Pindell et al, 2005). Its eastern part, the Venezuelan Basin, was apparently formed at a typical oceanic spreading center forming normal oceanic crust, but much of it later experienced another phase of deformation, including the addition of a layer of volcanics ontop of the original crust and sediments, leading to a total crustal thickness of about 10 km (Diebold et al., 1999). As the Caribbean oceanic crust south of Puerto Rico is estimated to have formed about 140Ma (Gosh et al., 1984), it presently lay some 2 km shallower than it should for its age. That is, the Caribbean lithosphere is buoyant when compared to normal oceanic lithosphere.

Local Seismic Recording and Seismic Velocity Models

Local recording of earthquakes in the Puerto Rico Virgin Island region began in 1974, and by 1977 some 30 station were in operation from Mona Island through the Virgin Islands (Figure 2). Recording was done by two different entities, and the details of those operations are given by Tarr and Davids (1977), Murphy and McCann (1979), and McCann (2002). Information on the existing network may be found at http://redsismica.uprm.edu/english/. Most early stations were single component verticals with a 1 or 2 Hz seismometer, analog signal transmission, and analog recording. By 1980, many stations had two components each, and finally three, and events were recorded digitally, significantly improving the quality of picks of P and S-wave arrival times.

Several special projects collected supplementary information useful for the development of seismic velocity models. In 1976, 1979 and 1982, several multi-ton calibration shots were detonated near the Puerto Rico Trench, and several other smaller shots were detonated, especially in the Anegada Trough and near the Virgin Islands segment of the subduction zone. Additionally, short-term ocean bottom seismometers were deployed, and refraction profiles shot. In the Virgin Islands portion of the network, Fischer and McCann (1984), used three multi-ton calibration shots and 160 earthquakes with depths of 0 to 85 km, to obtain a velocity model by inverting data for hypocenters, velocities and station delays. They used a version of the program *Velin* by Crosson (1976), which determines seismic velocities for layers of fixed thickness. Even with the limited nature of that effort, the new velocity model allowed for much improved event locations, led to the discovery of two crustal faults near Saint Thomas, and found that many station delays correlate with surface geology. The large delays for stations on the island of Saint Croix (0.4 to 0.9 sec) remained unexplained and the three multi-ton calibration shots used in the inversion had mislocation errors as large as 17 km. Whitmarsh et al. (1983) reports on investigations in the nearby Northern Lesser Antilles.

Asencio (1980) reports on three methods used to estimate the crustal and sub crustal seismic velocities near Puerto Rico. Those methods were: 1- study of refracted arrivals from earthquakes lying outside the USGS Puerto Rico network; 2- modeling the crustal structure using events within the network; and 3-seismic refraction and gravity data. The result of these efforts was the determination of Vp/Vs=1.778, and a composite crustal model of Vp=6.37 km/sec to 15.79 km depth, 7.52km/sec to 27.37 km depth and 8.13 km/sec for the mantle. Huerfano and Bataille (1994) developed two models based on reduction of *rms* values and inversion of arrival times. These new models have generally slower crustal velocities and a mantle velocity of 7.9 km/sec starting about 20 Km depth.

Data Selection and analysis

Locally recorded earthquakes with arrival times between 1974 and 2000 composed the database available for this study. As a first cut, events south of 19.0°N and north of 17.5°N with 6 or more stations with P-wave arrivals of quality 3 or better were selected. That group of events was then divided geographically; those from 65.5° to 67.5°W were used to develop the model for Puerto Rico those from 65.5°W to 63.5 were used for Virgin Islands modeling. Because of the limited number of events, no restriction was placed on event depth in the Virgin Islands. However, in the Puerto Rico region, events in the upper 50 km were used. Events were found as deep as about 150 kilometer in both regions.

Inversion for Seismic Velocities - Puerto Rico

For the Puerto Rico region the station LSP was chosen as the reference station, and although is does not near the geographic center of the model region, it does lie in the region of highest shallow seismicity. Events with 8 or more arrival were selected (Figure 2a). Some events had as many as 19 station reporting P-wave arrival times. Forty-six stations reported arrival times. Nearly 5500 readings were used in the inversion. The FORTRAN program *Velest* (Kissling, 1988, 1994, 1995) was used to simultaneously invert events hypocenters, origin times, travel times to stations, station delays and P-wave velocities for a minimum model rms. Events were first allowed to shift location in a fixed model and fixed station delays, and then station delays and layer velocities were allowed to change. No low-velocity zones were permitted. As noted above, there are several estimates of seismic velocities for the crust and upper mantle region near Puerto Rico. Each of those models, three from Asencio (1980) and two from Bataille and Huerfano (1995) were used as starting models for the inversion in *Velest*. The original models of Asencio (AI, AG,AR) and Bataille and Huerfano (BI, BR) are composed of few, relatively thick layers (Figure 3a). The corresponding starting *Velest* models were composed of several layers 2 to 4 km thick extending from the highest station at 1.3 km above sea level, down to 36 kilometers. Appropriate V_p velocities were assigned to each layer from the given starting model. After several (usually 5) iterations, the interim model was checked for layers with the same P-wave velocity. Any such layers were combined into a single layer and the inversion process repeated. Once it was found that no more layers were to be combined, then each layer boundary was varied in 1 km steps, shallower and deeper, in search for a lower *rms* solution. This search started with the lowest boundary and proceeded shallower.

The five starting models provide sufficiently different velocity structures to test the reasonableness of any result from *Velest*. Surface velocities vary from as low as 4.5 km/sec (model BR) to as high as 6.37km/sec (model AR). Initial crustal thickness varied from 21 to 34 km. All final models indicate near surface V_p of 6.0 km/sec or higher, lower crustal velocities near 7.0 - 7.25 km/sec and a total crustal thickness of at least 31 km (figure 3b, Tables 1, 2). The preferred model, best in terms of *rms*, is that achieved starting with model AI. It is a simple 2-layer model over a half space.

Station delays of similar magnitude and sign for this preferred model are generally spatially grouped. LSP, the reference station lies in Western Puerto Rico in the geologically distinct SW province (Figure 4). Six other stations also lie in that province and their delays are +/-0.25 except for MPR, who had relatively few reading and whose delay may therefore be poorly constrained, and PORP. Most of the stations northwest of the Great Southern

Puerto Rico Fault Zone and in the Northern or Central Provinces noted earlier, have delays slightly negative (-.25 to –0.5) to strongly negative (-0.0 to –0.75), suggesting that the SW province is composed of material with generally lower compressional wave velocities when compared with the rest of the island. Three stations in the northwest part of the island have more positive delays, which may be due to the approximately 2 km thick layer of late tertiary sediments found along the north coast (Monroe, 1980). Variations in that total sediment thickness is caused by basement relief (Larue et al., 1998) and north coast geophysical studies suggest as much as 4-5 km of sediments near the station APR.

Inversion for Seismic Velocities – Virgin Islands

Previous velocity models for the Virgin Islands region are few. Officer et al., (1959) presented a several refraction profiles for this part of the island chain. The models were as varied as the tectonics of this complex region. Fischer and McCann (1984) inverted several profiles of earthquakes extending from a certain network station to one of several multi-ton shots above the Puerto Rico megathrust to develop a model for the region north of the main portion of the network. In this investigation, the distribution of stations and earthquakes is such that the crust and mantles sampled by the illuminating rays lies generally to the south of the region sampled by McCann and Fischer, so the results will not be directly comparable. Nevertheless, the average model of Fischer and McCann (1984) was used as a starting model. Other starting models were constructed to sample the possibility that shallow crustal velocities were in the range 5.5 to 6.5 km/sec and that upper mantle velocities were in the range 7.5 to 8.2 km/sec.

Although there is a wide range of shallow crustal velocities in the starting models, 4.5-6.0 km/sec, all four models converged to velocities near 6.0 km/sec for the upper 10km (figure 5a,b, Tables 1,3). While there is some variation in the lower crustal velocities and layer thicknesses, all models give a total crustal thickness of 24-32 km with upper mantle velocities in the range 7.5-7.8 km/sec. When comparing these results with those for Puerto Rico, several points should be noted: 1- It is known that the region investigated in the Virgin Islands is more structurally complex than Puerto Rico; 2- There are significantly fewer events for the Virgin Islands region; 3- The data variance and rms for the final Virgin Islands models are higher than those of Puerto Rico perhaps reflecting structural complexity; 4- Upper mantle velocities are significantly lower in the Virgin Islands than in Puerto Rico (7.93-8.18 km/sec).

Seismic Sources with Controlled Locations and/or Origin Times: Relative and Absolute location errors

Several controlled seismic sources were used to calibrate and verify the results of *Velest* (Figure 2a,b). As they were not used as fixed sources in the inversion process, they provide an independent measure of relative and absolute location errors, that is, how well the new model represents the real earth and how well natural earthquakes would be located by using this new model.

Quarries in Puerto Rico- Puerto Rican law permitted the detonation of large explosions for quarrying purposes. Quarries are in the south, west and north of the Puerto Rico. Also, large blasts were also set off during the construction of the islands major highways. The USGS, in its analysis of PR network data for 1975-1977 noted several known

and probable blasts (Dart et al., 1977). These events were well recorded by the network having sufficient data to provide locations using normal location procedures. Shallow events near known quarries cluster in space and time; locations being very shallow and at times exclusively during Weekdays 6am-6pm, local time with the vast majority of events occurring from 2-4 pm. These quarry blasts can have their locations constrained, but with origin times unknown. To test the ability of the new seismic velocity model to accurately locate local, shallow earthquakes we investigated shallow seismic events in the quadrangles of Aguas Buenas and Naranjito. This is where the USGS identified many as probable blasts. Topographic maps of those quadrangles show three closely spaced quarries at the eastern edge of the Naranjito quadrangle (Figure 7).

Sixty–five events were well-recorded, located near those quarries, occurred 1975-1978 during daylight hours on weekdays. The origin times of these events strongly cluster about 1706UT and 2018UT, which are about 1pm and 4pm local time, respectively (Figure 8). They are considered possible blasts. All these events were located using the same starting location at one of the quarries, and the Puerto Rico P- and S- wave velocity models derived in *Velest*. Final event locations are strongly biased to the south and west of the quarries. All events had final locations at the surface. While we don't know which of the three quarries produced which events, it is clear that the events that occurred around 1700 UT are in general located farther south than those that occurred around 2000 UT. Events occurring around 2000 are found from 0 –2 km mostly SW of the quarries, whereas the 1700 events are 1 – 2 km in a broader area west and south.

Airport Construction on Saint Thomas- During the height of operation of the NE Caribbean Seismic Network construction began on the expansion of the Airport on Saint Thomas. In order to accommodate the new terminal building, a large hill had to be leveled, and another partially removed. Blasting to remove those hills produced artificial seismic events recorded by several seismic stations in the Virgin Islands. While the blast times are not known, the latitude, longitude and elevation of those blasts sites are known. While we do not have origin times or specific coordinates for each of the blasts we do know that they were first conducted on Cabritaberg Hill in late 1979 and activity later moved to the more easterly Sarah Hill in 1980 (C and S respectively in Figure 9; W. Bostwick, written comm., 2004). We also know that shots were done in daylight, on weekdays, with approximately the same size charges. Much more work was done on the first hill, then some on the second (oral comm., A. Roman, 2004). Considering this information, I selected shallow events in the network catalog for late 1979 into 1980 6am-6pm local time, weekdays, within 20km of the VST, a station near the airport (figure 9).

After the development of the new model for the Virgin Islands, events selected as possible airport construction blasts, were located using *Velest* in JHD mode. Initial event locations were set at the westernmost of the two possible blast sites. Final locations form an ellipse whose center is just north of that blast site, and with a semi minor axis of about 500 meters from the longitude of the blast site, and semi major axis reaching about 1 km to the south and 2 km to its north. Of the fourteen blasts, three were located deeper than one-kilometer depth (blasting occurred at about 100 meter above sea level). No events fall near or east of the second blast sites, even though they occurred late in the period of blasting.

8

Conclusions

Two new seismic wave velocity models were developed for the Puerto Rico Virgin Islands in the US Caribbean from over 5,000 arrivals times registered by a local seismic network. We developed a new catalog of 18,000 locally recorded earthquakes from 1975-2001 located using the same velocity model thereby standardizing the location of events for the last 25 years. Station delays in Puerto Rico suggest differences between the SW geologic province and the other two provinces. For the Virgin Islands, although the model does not seem to be as well determined as in Puerto Rico, it does show a thinner crust and much lower P-wave velocities in the upper mantle when compared to the crustal structure to the West.

Quarry and construction blasts provide information about the relative and absolute location errors using these new models. In Puerto Rico quarry event have an absolute location bias to the west and south of about 1-2 km. Most events locate at or near the surface. In the Saint Thomas, events are biased to the west of the blast source by about 500meters and are spread out in a north-south direction with dimension of 3 kilometers. Most events locate near the surface.

Acknowledgements

References

Asencio, E., 1980, Western Puerto Rico Seismicity, U.S. Geological Survey Open File Report 80-192, 135p.

Byrne, D.B., Suarez, G., and McCann, W.R. 1985. Muertos Trough subduction-microplate tectonics in the northern Caribbean?.Nature. Vol. 317.6036:420-421.

Crosson, R.S., 1976, Crustal structure modeling of earthquake data,1, Simultaneous least squares estimation of hypocenter and velocity parameters, J. Geophys. Res., 81, 3036-3046.

Dart, Richard L; Carver, David; Wharton, Mary Kay; Tarr, Arthur C (1979): Puerto Rico Seismic Program Seismological Data Summary July 1,1975- December 31,1977. Open File Report 79-870.1979.

Deng and Sykes (1995): Determination of Euler Pole for contemporary relative motion of Caribbean and North American Plates using slip vectors of interplate earthquakes, Tectonics, 14, 39-53.

Diebold, J., and N. Driscoll, 1999, new Insights on the formation of the Caribbean Basalt Province Revealed by Multichannel Seismic Images of Volcanic Structures in the Venezuela Basin, in *Caribbean Basins. Sedimentary basin of the world*, 4 edited by P. Mann, pp561-589.

Donnelly, T., 1966, Geology of St, Thomas ands St,. John, US Virgin Islands, In Hess, H. H., ed., Caribbean Geological Investigations: GSA Memoir 98, p. 85-176,

Ellsworth, W., Three Dimensional Structure of the crust and mantle beneath the island of Hawaii, Ph D Thesis, MIT Massachusetts, USA, 1977

Fischer,K; McCann,W (1984): Velocity modeling and Earthquake Relocation in the NE Caribbean, Bull. Seism. Soc. Amer., 74, 1249-1262.

Garrison L. E. (1972): Acoustic-Reflection profiles, Eastern Greater Antilles, IDOE Leg 3, U.S. Geol. Survey. GD-72-004, NTIS PB2-07596, 33p.

Gosh, N., Hall, S., and Casey, J., 1984, Seafloor spreading magnetic anomalies in the Venezuela basin, The Caribbean-South American Plate Boundary and Regional Tectonics, 16:65-80

Huerfano, V, and K. Bataille, Appendix A: Crustal Structure and stress regime near Puerto Rico, in Seismic Bulletin, Preliminary Locations of Earthquakes Recorded near Puerto Rico Jan-Dec 1994, published 1995, 15-19.

Huerfano, V., Bataille, K., 1994, Crustal structure and stress regime near Puerto Rico, Seismic Bulletin, Jan-Dec 1994, PRSN, Mayaguez, PR., 403p.

Jansma, P. and 6 other authors, 2000, Neotectonics of Puerto Rico and the Virgin Islands, northeastern Caribbean, from GPS Geodesy, Tectonics, 19 (6), 1021-1037.

Jansma, P., Mattioli, G., 2005, GPS Results, from Puerto Rico and the Virgin Islands: Constraints on tectonics setting and rates of active faulting, in Mann ed., Active tectonics and seismic hazards of Puerto Rico, the virgin islands, and offshore areas: GSA special paper 385, p13-30.

Jany, A. Mauffret, P. Bouysse, A. Mascle and 3 other authors, Seabeam survey and wrench tectonics south of the Virgin Islands, 1987, C. R. Acad. Sc. Paris, t. 304, Serie II, #10.

Jolly, W.T., Lidiak, E.G., Schellekens, J.H., Santos, H., Lidiak, E.G., and Larue, D.K., 1998, Volcanism, tectonics, and stratigraphic correlations in Puerto Rico, (eds.), Tectonics and geochemistry of the northeastern Caribbean, Special Paper , 322: 1-34,

Kissling, E., 1995, Program VELEST users Guide-Short Introduction, Internet version.

Kissling, E., Ellsworth, W., Ebert-Phillips, D., U. Kradolfer, 1994, Initial reference models in local earthquake tomography, J. Geophys., Res, 99, 19,635-19,646.

Kissling, E., Geotomography with local earthquake data, Rev. of Geophysics, 1988.

Ladd, J., Worzel, J., and Watkins, J., 1977, Multifold seismic reflection records from the northern Venezuelan Basin and the northern slope of the Muertos Trench, in M. Talwani and W.C. Pitman, III (eds.), Island Arcs, Deep Sea Trenches, and Back-arc Basins, Maurice Ewing Series, 1: 41- 56, American Geophysical Union, Washington, D.C.

Ladd, J.W., and Watkins, J.S., 1978, Active margin structures within the north slope of the Muertos Trench, in H.J. MacGillavry and D.J. Beets (eds.), Transactions of the 8th Caribbean Geological Conference, Curaçao, 57: 255-260, Geologie en Mijnbouw, v. 57, p. 97-384, Delft, Netherlands.

LaForge, R.C., and McCann, W. R., 2003, A Seismic Source Model for Puerto Rico, for use in Probabilistic Ground Motion Hazard Analyses, submitted to Geological Society of America Special Paper: Active Tectonics & seismic hazards of Puerto Rico and the Virgin Islands, edited by P. Mann and C. Prentice.

Larue, D. K., R. Torrini, A. Smith, J. Joyce, 1998, North Coast Tertiary Basin of Puerto Rico: From Arc Basin to Carbonate platform to arc massif slope, in Tectonics and Geochemistry of the northeastern Caribbean eds E. Lidiak and D. Larue, GSA SP 322. p155-176.

Lithgow, C.W., McCann, W., and Joyce, J., 1987, Extensional tectonics at the eastern edge of the Puerto Rico Platelet: Eos (Transactions, American Geophysical Union), v. 68, p. 466–489.

Mann, P., E. Calais, J.-C. Ruegg, C. DeMets, P. E. Jansma, and G. S. Mattioli, Oblique collision in the northeastern Caribbean from GPS measurements and geological observations, Tectonics, 21(6), 1057, doi:10.1029/2001TC001304, 2002.

Matthews, James E; Holcombe,Troy L (1976): Regional Geological /Geophysical Study of the Caribbean Sea (Navy Ocean Area NA-9). Naval Oceanographic Office Reference Publication RP 3, 1976.

McCann, W., 1998, Tsunami Hazard of Western Puerto Rico from Local Sources: Characteristics of Tsunamigenic Faults, Seagrant internal report, Univ. of PR, Mayaguez, Dept of Marine Sciences, 82p.

McCann, W., 2002, Microearthquake data elucidate details of Caribbean subduction zone, Seismol. Res. Letters, 73, 25-32.

McCann, W.R. 1985. On the earthquake hazards of Puerto Rico and the Virgin Islands. B.S.S.A., Vol.75,1:251-262.

Molnar, P. and Sykes, L.R. 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. Geological Society of America Bulletin, v.80, p.1639-1670.

Monroe, W., Geology of the Middle Tertiary Formations of Puerto Rico, U.S.G.S. Professional Paper 953, 93 pp. 1980.

Mueller, C., Frankel, A., Peterson, M., and E. Leyendecker, 2003a, Documentation for 2003 Seismic Hazard Maps for Puerto Rico and US Virgin Islands, preprint

Mueller, C., Frankel, A., Peterson, M., and E. Leyendecker, 2003b, Probabilitstic Seismic Hazard Maps for Puerto Rico and the US Virgin Islands, SSA Annual Meeting, Abstracts, Seism. Res. Letters, Vol. 74, p207.

Muller, R., Royer, J., Cande, S., Roest, W., and Maschenkov, S., 1999, New Constraints on the Late Creatceous/Teritary Plate Tectonic Evolution of the Caribbean, in P. Mann, ed., Caribbean Basins, Sedimentary Basins of the World, p33-59.

Murphy, Andrew J, McCann, William R (1979): Preliminary Results From A New Seismic Network In The Northeastern Caribbean. Bull. Seism. Soc. Amer., 5 69, 1497-1513.

Officer, C; Ewing,J; Hennion,J; Harkrider,D; Miller,D (1959): Geophysical investigations in the eastern Caribbean-summary of the 1955 and 1956 cruises. L. Ahrens et. al. Physics and Chemistry of the Earth, V.3: London, Pergamon Press,464 p.

Officer, CB; Ewing,JI; Edwars,RS; Johnson,HR (1957): Geophysical Investigations in the Eastern Caribbean: Venezuelan Basin,Antilles Island Arc, and Puerto Rico Trench. Geol. Soc. America Bull 68, 359-378.

Pindell, J, L. Kennan, K.-P. Stanek, W.V. Maresch, and G. Draper, , 2006, Foundation of Gulf of Mexico and Caribbean Evolution: Eight Controversies Resolved, Geologia Acta.

Rankin, Douglas, W., 1997, Geologic Maps of St. John U. S. Virgin Islands, USGS Open File Report 97-472.

Silver, E., 1972, Acoustic Reflection Profiles Venezuela Borderland, USGS-GD-72-005,

Talwani, M., G.H. Sutton, and J.L. Worzel, A crustal section across the Puerto Rico Trench, Journal of Geophysical Research, 64, 1545-1555, 1959.

Tarr, A. and K. King, 1976, Puerto Rico Seismic Program, U.S. Geological Survey, Open File Report 76-49, 23p.

Tarr, A. and N. Davids, 1977, Seismic Network Analysis Processing System (SNAPS):
System Design and User's Guide fro Hypocenter Determination, OFR 77-268, 66p
Whitmarsh, R. B., Keen, C. E., Steinmetz, L., Tomnblin, J., Donegan, M., Lilwall, R. C.,
Loncarevic, B. D., Nichols, B., and J. Shepherd. A lithospheric Seismic Refraction
Profile in the Western North Atlantic Ocean, Geophys. J. R. Astr. Soc, 1983, v75, 23-
69.

Table 1a. Final, Preferred Models from *Velest* Inversion

Model	Vp (km/sec)	Vs (km/sec)	Vp/Vs	Top of Layer (Km)
PR-AI	6.45	3.62	1.78	-5
	7.13	4.16	1.71	17
	8.01	4.61	1.74	31
VI-S	5.97			-5
	6.08			3
	6.37			12
	6.67			16
	7.61			29

PR-AI is new model for Puerto Rico; VI-S is new model for the Virgin Islands

Table 1b. Results of Nine starting models for *Velest* Inversion

Region	Starting Model	Final Data Variance	Mean Sqrd Residual	Final RMS
Puerto Rico	**AI**	**0.1107**	**0.0634**	**0.2517**
	BR	0.1097	0.0637	0.2523
	AG	0.1130	0.0647	0.2543
	AR	0.1147	0.0657	0.2562
	BI	0.1160	0.0663	0.2575

Region	Starting Model	Final Data Variance	Mean Sqrd Residual	Final RMS
Virgin Islands	**S**	**0.4552**	**0.2332**	**0.4829**
	H	0.4571	0.2344	0.4841
	N	0.4596	0.2355	0.4853
	B	0.4610	0.2364	0.4862

Note: Preferred model is in Bold.

Table 2. Station results for Puerto Rico model AI

Station Parameters Puerto Rico Model AI

Sta	lcc	Latitude	Longitude	Elev (m)	Nparr	Avres	Avwres	Std	Wsum	P correction (sec)
abv	20	*18.7320*	*-64.3370*	*3*	*16*	*0.009*	*0.022*	*0.71*	*7*	*0.38*
agp	21	*18.4078*	*-67.1403*	*222*	*11*	*-0.018*	*0.000*	*0.08*	*12*	*0.04*
apr	24	18.4575	-66.7293	53	439	-0.003	0.001	0.20	411	-0.04
cbyp	64	18.2700	-65.8600	550	79	0.001	0.002	0.23	75	-0.35
cca	28	18.0697	-66.3263	269	59	-0.019	0.002	0.21	71	-0.31
cdp	29	18.1750	-66.5917	1300	138	-0.006	0.000	0.26	135	-0.48
celp	65	18.0746	-66.5795	195	178	-0.019	**-0.020**	0.18	190	-0.30
cgpv	67	*17.7635*	*-64.5837*	*40*	*16*	*0.028*	*-0.005*	*0.24*	*7*	*-0.33*
cgv	30	*18.1328*	*-65.3173*	*130*	*17*	*-0.016*	*-0.003*	*0.22*	*23*	*-0.32*
cllp	65	18.0800	-66.5767	195	202	0.023	**0.018**	0.17	236	-0.30
corn	69	*18.1635*	*-67.1793*	*8*	*2*	*0.018*	*0.000*	*0.03*	*1*	*0.01*
cpd	31	18.0388	-65.9152	370	449	-0.002	0.002	0.20	400	-0.44
csb	32	18.2892	-66.1558	480	454	-0.014	0.003	0.26	415	-0.53
csj	33	18.3830	-65.6180	66	23	0.016	-0.002	0.27	28	-0.03
cup	34	18.3350	-65.3090	120	35	-0.019	0.003	0.28	35	-0.24
cyp	35	*18.1117*	*-66.1500*	*457*	*10*	*0.038*	*0.000*	*0.27*	*6*	*-0.52*
eyp	37	*18.3125*	*-65.7917*	*1060*	*16*	*-0.028*	*-0.003*	*0.16*	*11*	*0.15*
gpv	38	*18.4920*	*-64.4040*	*342*	*18*	**0.755**	*0.000*	*0.41*	*10*	*-0.16*
ide	39	18.3865	-67.4962	218	86	-0.027	-0.001	0.15	84	-0.09
imo	40	18.1115	-67.9085	84	27	-0.051	0.000	0.13	19	-0.32
imr	41	*18.0883*	*-67.8472*	*55*	*7*	**-0.273**	*0.000*	*0.19*	*4*	*-0.39*
lpr	42	18.3087	-65.8693	580	205	0.005	0.003	0.20	166	-0.53
lrs	43	18.2933	-66.8450	440	391	-0.004	0.000	0.18	413	-0.32
lsp	999	18.1775	-67.0860	390	459	-0.003	0.000	0.18	480	0.00
mcp	45	18.4188	-67.1105	250	180	-0.001	0.000	0.18	227	0.02
mep	46	18.1497	-66.9833	888	24	-0.001	0.001	0.11	21	-0.17
mgp	47	18.0075	-67.0892	60	490	0.013	0.001	0.17	543	-0.08
moca	70	18.4143	-67.0075	250	71	0.021	-0.001	0.39	72	0.46
mov	49	18.2820	-66.3667	485	45	0.011	0.000	0.26	41	-0.35
mpr	50	*18.2127*	*-67.1392*	*20*	*8*	**0.398**	*0.000*	**1.22**	*9*	*0.35*
mrn	51	*18.0120*	*-63.0600*	*20*	*7*	*0.100*	*-0.001*	*0.34*	*4*	*-0.57*
mtp	52	18.0940	-65.5570	175	31	0.085	**0.008**	0.36	56	-0.16
pnp	53	18.0597	-66.7667	200	345	0.004	0.001	**0.49**	390	-0.03
porp	75	18.0538	-66.6370	165	356	0.001	0.000	0.19	369	-0.31
pwp	55	*18.1350*	*-65.4450*	*10*	*11*	**-0.150**	*-0.001*	*0.47*	*4*	*0.36*
rrd	56	18.2360	-65.6180	40	22	-0.017	-0.004	0.43	37	-0.20
scv	58	17.7817	-64.7890	12	22	**0.276**	**-0.009**	0.44	7	-0.42
sjg	59	18.1117	-66.1500	457	330	0.012	0.002	0.17	314	-0.41
sjgc	59	18.1117	-66.1500	457	129	-0.052	0.000	**0.55**	101	-0.41
sjv	60	18.3450	-64.7620	280	30	0.047	-0.001	0.33	22	-0.13
vst	61	18.3540	-64.9570	372	32	0.134	**0.012**	0.34	13	-0.27

Note: Values in italics are poorly determined as a result of few arrivals for that station. Bold

values are outliers when compared with all other results.

Table 3. Station Results for Virgin Islands Model S

Station Parameters Virgin Islands Model S

Sta	lcc	Latitude	Longitude	Elev (m)	Nparr	Avres	Avwres	Std	Wsum	P correction (sec)
abv	20	18.7320	-64.3370	3	248	0.01	0.001	0.26	233	0.19
apr	24	18.4575	-66.7293	53	27	0.04	0.005	**0.92**	17	-0.50
awin	*62*	*17.0450*	*-61.8600*	*371*	*9*	*-0.01*	*0.001*	*0.18*	*8*	*-1.95*
bwi	*26*	*17.6650*	*-61.7900*	*36*	*8*	*0.07*	*0.002*	*0.08*	*3*	*-2.13*
cca	*28*	*18.0697*	*-66.3263*	*269*	*16*	*0.10*	*0.001*	***1.10***	*14*	*0.86*
cdp	29	18.1750	-66.5917	1300	55	**-0.34**	-0.003	**1.02**	33	-0.66
cgpv	67	17.7635	-64.5837	40	304	0.01	0.003	0.18	224	0.21
cgv	30	18.1328	-65.3173	130	249	-0.01	0.001	0.32	204	0.21
cpd	31	18.0388	-65.9152	370	71	-0.15	0.003	0.77	84	0.76
csb	32	18.2892	-66.1558	480	75	-0.09	0.005	0.69	70	-0.29
csj	33	18.3830	-65.6180	66	313	0.03	0.002	0.67	233	-0.23
cup	34	18.3350	-65.3090	120	417	-0.03	0.002	0.46	402	0.09
cyp	*35*	*18.1117*	*-66.1500*	*457*	*6*	***-0.21***	***0.023***	*0.30*	*4*	*0.34*
eyp	37	18.3125	-65.7917	1060	21	0.03	0.003	0.35	12	-0.34
gpv	38	18.4920	-64.4040	0	263	-0.05	0.001	0.12	281	-0.15
ide	*39*	*18.3865*	*-67.4962*	*218*	*2*	*-0.16*	*0.005*	*0.26*	*1*	*-1.21*
lpr	42	18.3087	-65.8693	580	61	-0.05	0.006	0.56	72	0.07
lrs	*43*	*18.2933*	*-66.8450*	*440*	*14*	*-0.09*	*0.001*	*0.52*	*13*	*0.02*
lsp	44	18.1775	-67.0860	390	50	0.00	**-0.008**	0.48	29	-0.41
mcp	45	18.4188	-67.1105	250	53	-0.19	-0.006	**1.64**	33	-0.79
mgp	47	18.0075	-67.0892	60	61	-0.05	0.000	0.45	42	-0.19
mov	*49*	*18.2820*	*-66.3667*	*485*	*11*	***0.52***	*0.001*	***0.91***	*9*	*0.53*
mrn	51	18.0120	-63.0600	20	91	0.11	0.002	0.12	81	-0.83
mtp	52	18.0940	-65.5570	175	359	0.01	0.002	0.59	412	-0.12
pnp	53	18.0597	-66.7667	200	68	-0.05	0.002	0.43	50	-1.05
pwp	55	18.1350	-65.4450	10	67	**0.22**	-0.001	**1.23**	62	-0.36
rrd	56	18.2360	-65.6180	40	186	0.03	0.002	0.26	138	-0.18
sbn	*57*	*17.6370*	*-63.2350*	*870*	*7*	*-0.01*	*0.001*	*0.14*	*2*	*-0.29*
scv	58	17.7817	-64.7890	12	232	0.11	0.000	0.34	173	0.33
sjgc	59	18.1117	-66.1500	457	77	-0.03	0.005	0.71	68	0.38
sjv	999	18.3450	-64.7620	280	442	0.00	0.000	0.33	774	0.00
skbr	*77*	*17.3410*	*-62.8400*	*0*	*14*	*-0.02*	*0.000*	*0.16*	*9*	*-0.42*
swip	*79*	*18.5980*	*-63.4260*	*15*	*9*	***0.72***	*0.000*	*0.28*	*4*	*-0.45*
vst	61	18.3540	-64.9570	372	404	0.05	0.000	0.41	500	0.07

Note: Values in italics are poorly determined as a result of few arrivals for that station. Bold

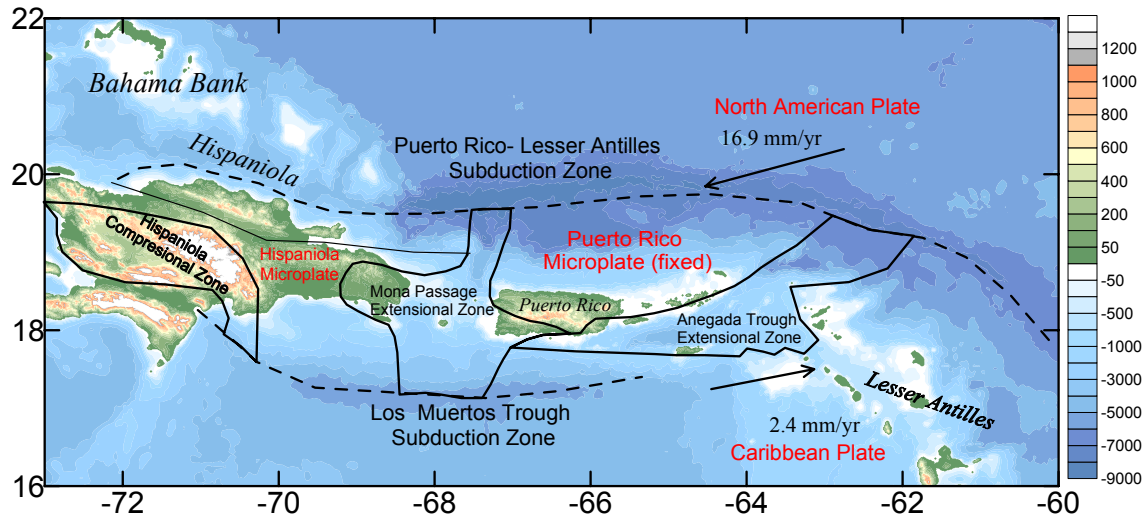values are outliers when compared with all other results.

Figure 1. General Tectonic model for area under investigation. The island of Puerto Rico lies at the eastern end of the Greater Antilles. The Puerto Rico microplate includes much of Puerto Rico and many of the smaller Virgin Islands to the east. The Puerto Rico microplate (fixed) experiences oblique convergence along its northern and southern margins, and extension along its eastern and western edges. Lithosphere from the North American Plate and Caribbean Plate are found beneath the island.
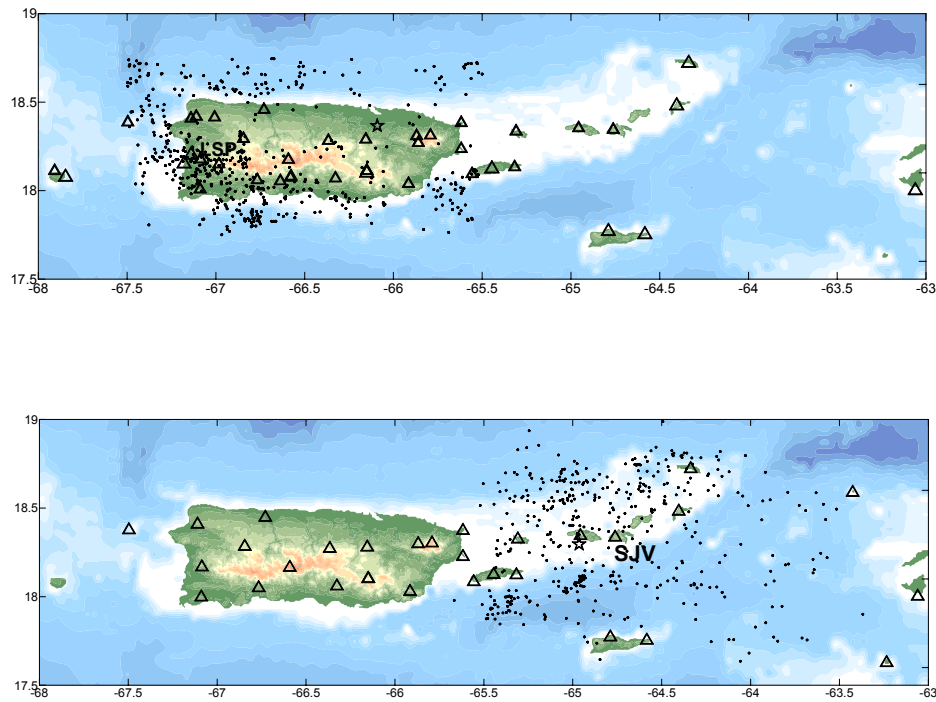

Figure 2a,2b Location of events used in Velest to develop new P-wave velocity models for Puerto Rico and the Virgin Islands. Triangles are locations of stations. Labeled stations (LSP and SJV) are reference stations with a fixed delay of 0.0 sec in the inversion process. Starts are location of artificial sources later used to estimate absolute and relative hypocentral errors.

Puerto Rico Starting Models

Velocity (km/sec)
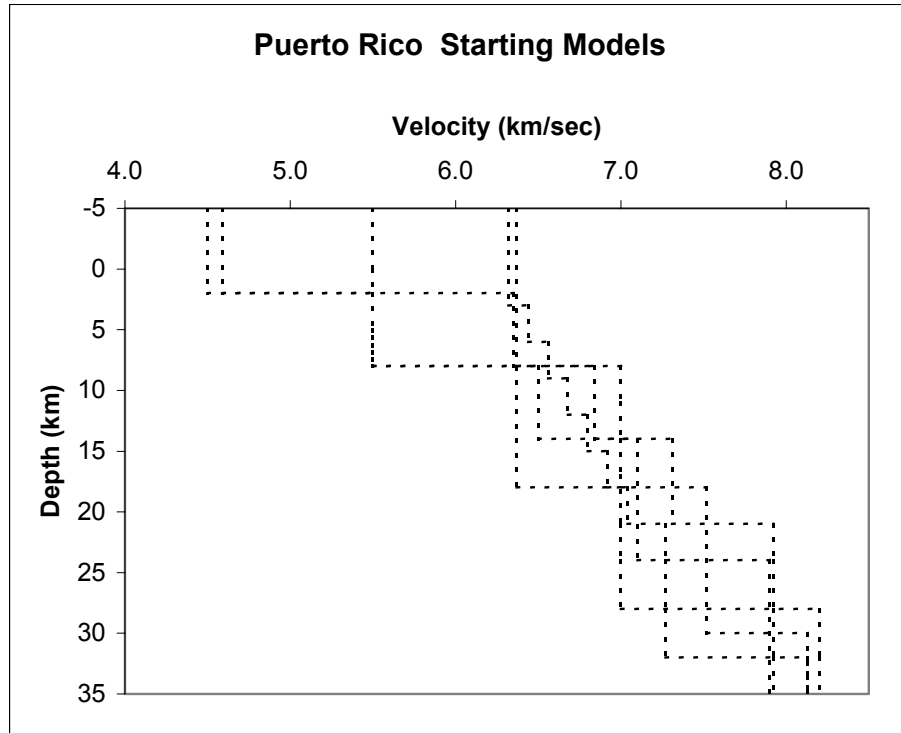
Figure 3a,b Starting and Final Models for Puerto Rico. Note the wide spread in starting velocities for the upper crustal region, and the wide range of crustal thicknesses. The final models suggest a crustal thickness of about 30 km with either two simple crustal layers or a fairly linear increase of velocities with depth. The preferred model is shown in bold. LSP is the reference station in each of these inversions.
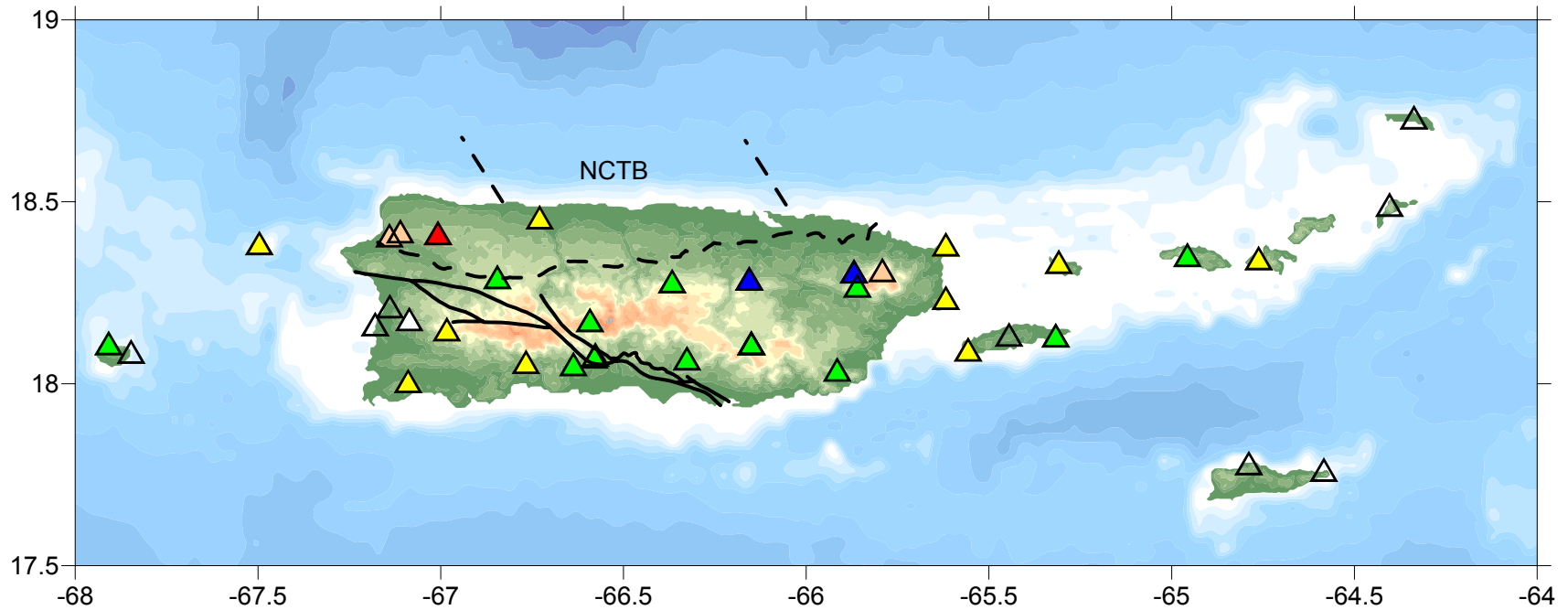
Puerto Rico Final Models

Velocity (km/sec)
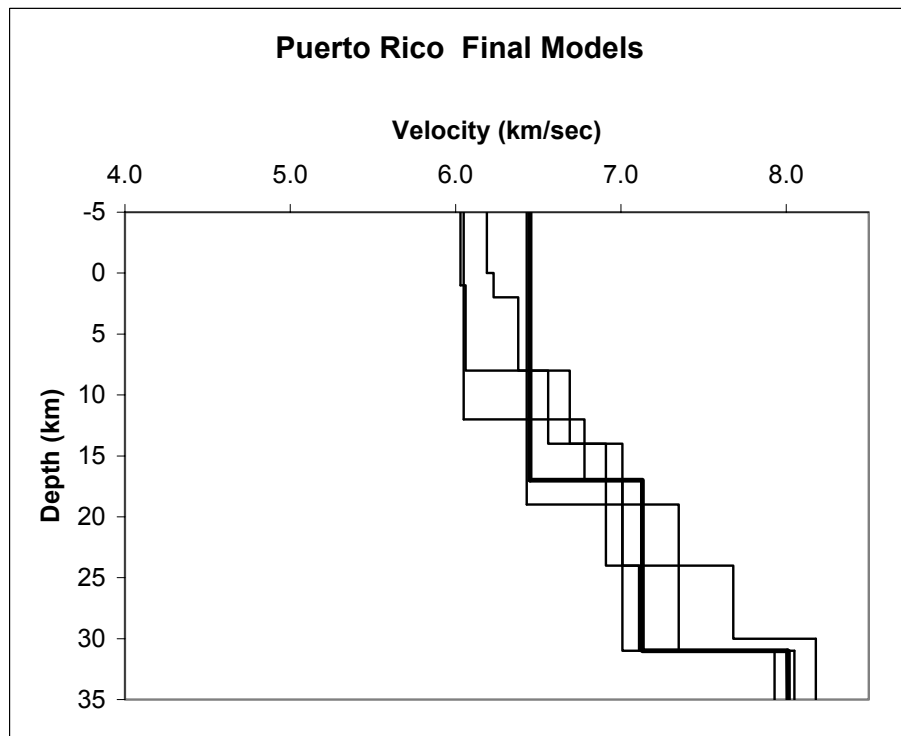
Figure 4. Station delays for Puerto Rico Model AI. NCTB and NW trending dashed lines are limits to north coast tertiary basin (NCTB) a thick deposit of relatively low velocity sediments. Dashed curve is limit of tertiary sediments overlying older volcanic units. Solid line is Great southern Puerto Fault Zone (GSPRFZ), separating the SW province from the central geologic province. Open triangles are stations with insufficient data to reliably determine a station delay. White triangle is reference station. Yellow, green and blue triangles are station with delays of 0 to -0.25, 0.25 to –0.5 and >-0.5 seconds respectively. Tan and red triangles are stations with delays of 0 to +0.25 and +0.25 to +0.5 seconds. Note spatial clustering in Puerto Rico of yellow (slightly slow) and green./blue stations (relatively fast) on either side of GSPRFZ. For those NW of the GSPRFZ, the slowest stations are those lying on tertiary sedimentary cover or in the NCTB stations.

VI Starting Models   SJV Reference Station
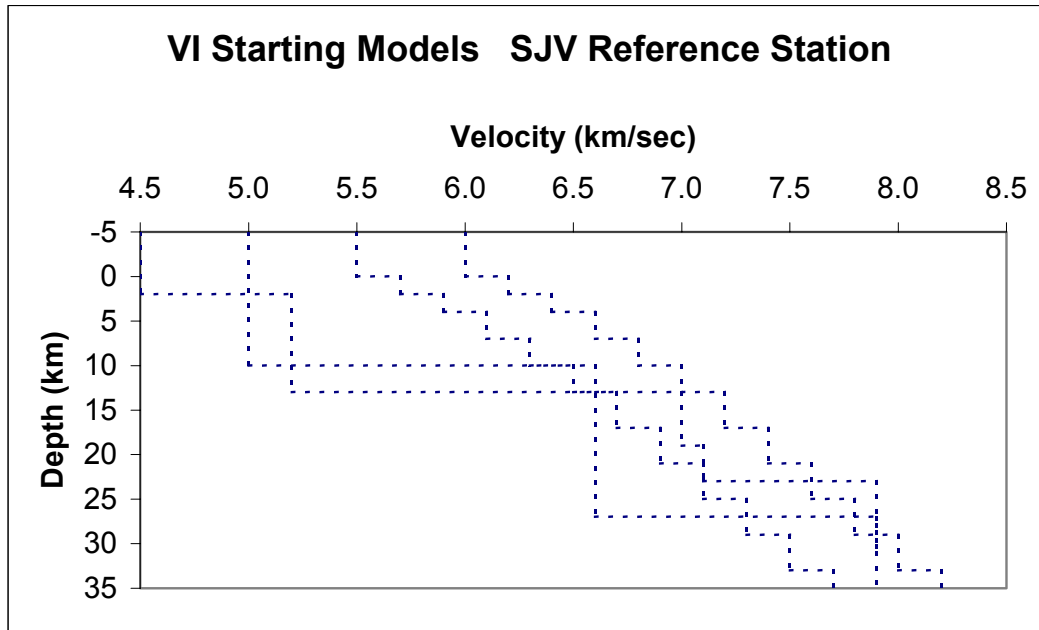
Velocity (km/sec)

Figure 5a,b Starting and Final Models for the Virgin Islands. Note the wide spread in starting velocities for the upper crustal region, and the wide range of crustal thicknesses. The final models suggest a crustal thickness of just less than 30 km with crustal layers P-wave velocities near 6.0 – 6.5 km/sec, then a jump to a low mantle velocity of about 7.6 km/sec. The preferred model is shown in bold. SJV is the reference station in each of these inversions.

VI Final Models SJV Reference Station

Velocity (km/sec)
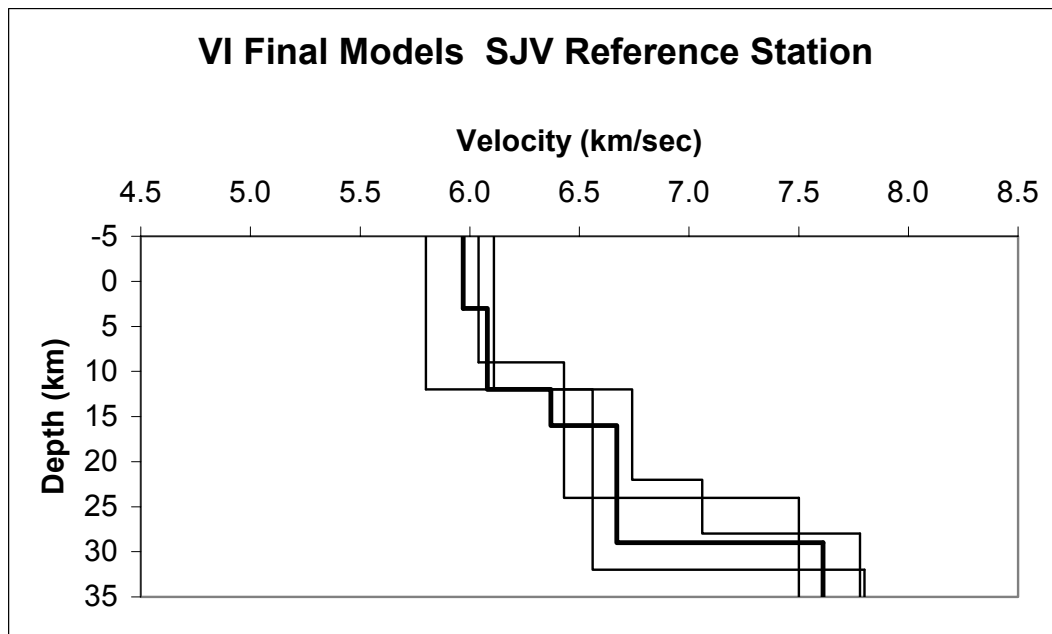
Virgin Islands Model S
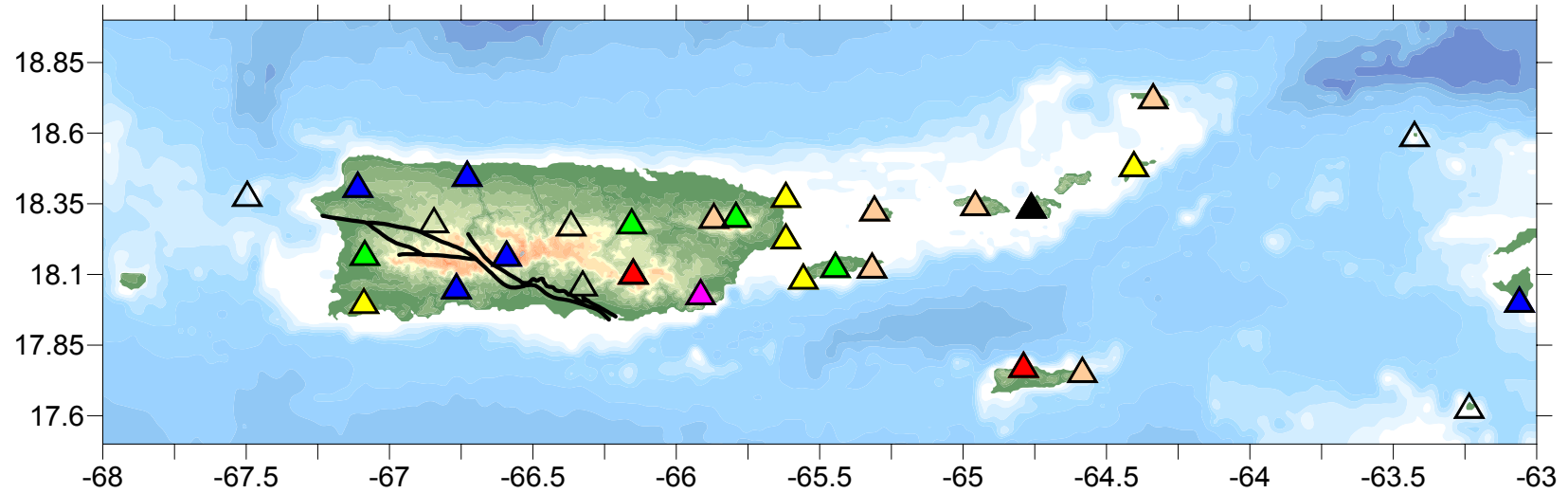
Figure 6. Station delays for Virgin Island Model S. Solid line is Great southern Puerto Fault Zone (GSPRFZ), separating the SW province from the central geologic province. Open triangles are stations with insufficient data to reliably determine a station delay. Black triangle is reference station. Yellow, green and blue triangles are station with delays of 0 to -0.25, 0.25 to –0.5 and >-0.5 seconds respectively. Tan and red and purple triangles are stations with delays of 0 to +0.25, +0.25 to +0.5, and >+0.5 seconds. Note spatial clustering in Virgin Islands of tan and yellow (slightly fast/slow) and green./blue stations (relatively fast) in Puerto Rico.
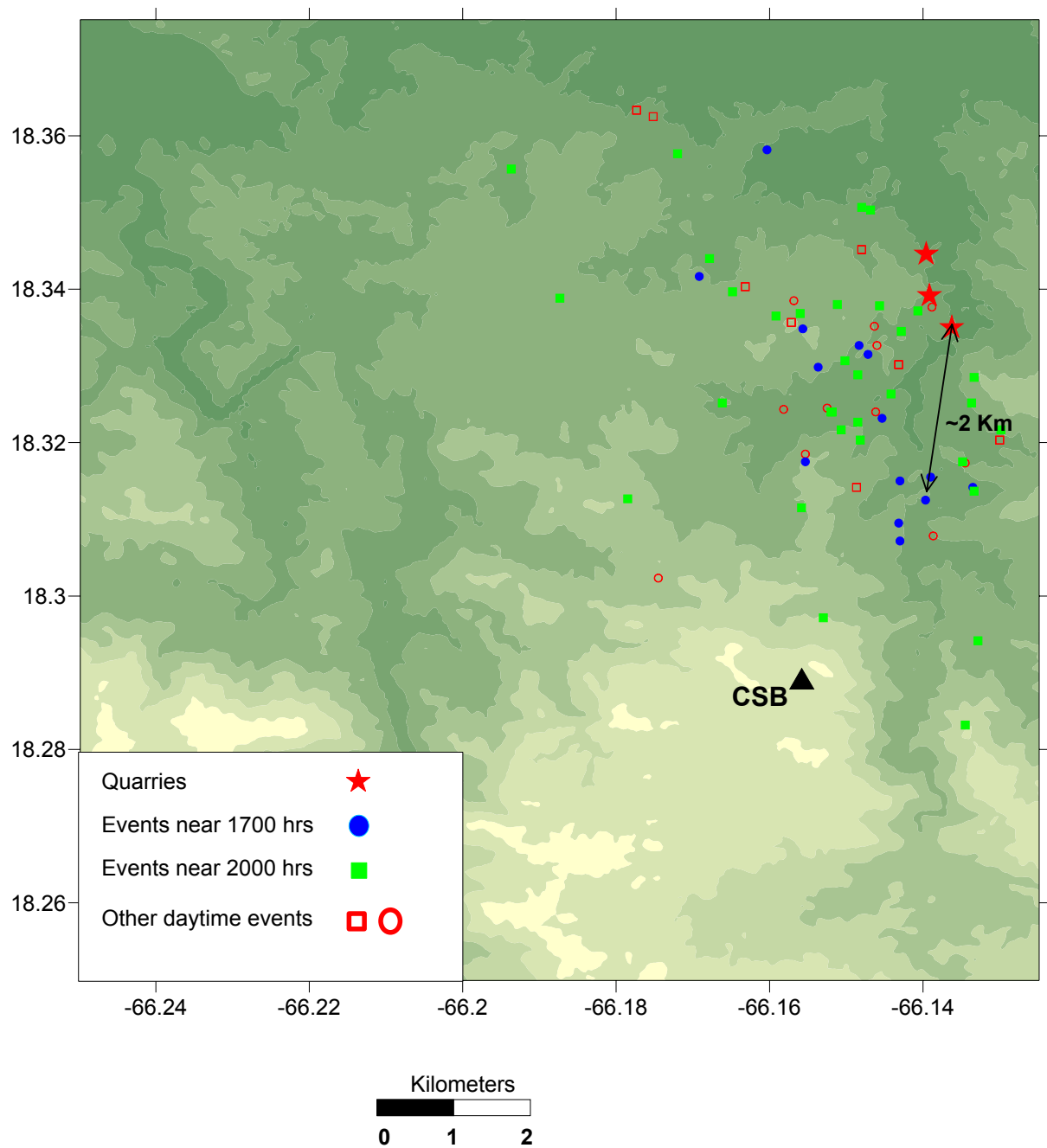
Figure 7. Artificial Seismic Sources for the period 1975-1978 in the Naranjito quadrangle (NW Puerto Rico). More than sixty quarry blasts occurred in that period. Events were located using *Velest* in JHD mode. Red stars are location active quarries; blue and green symbols are event occurring near 1700 or 2000 hour (UT). Blue event (1700) tend to locate more to the south of green ones (2000). Most events have an absolute location bias to the south and west of the quarries of 2 km or less.
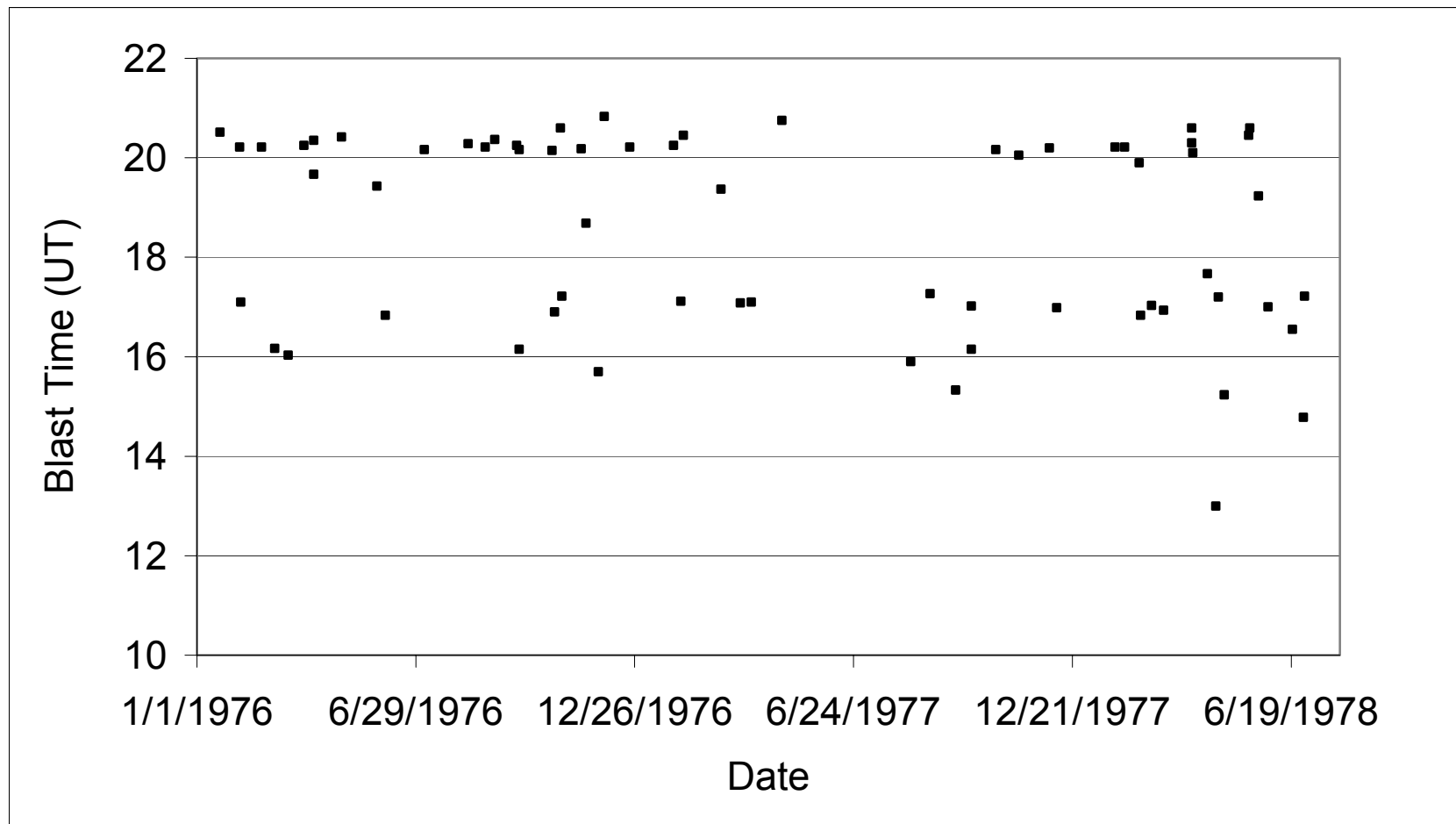
Figure 8. Computer origin times for all Monday-Friday, daytime (i.e. 1000-2200UT) sources in the Naranjito quadrangle for the time period under investigation. Note the lack of randomness of origin times. Clusters near 1700 and 2000 are clear, suggesting events are artificial and related to nearby quarrying activity.
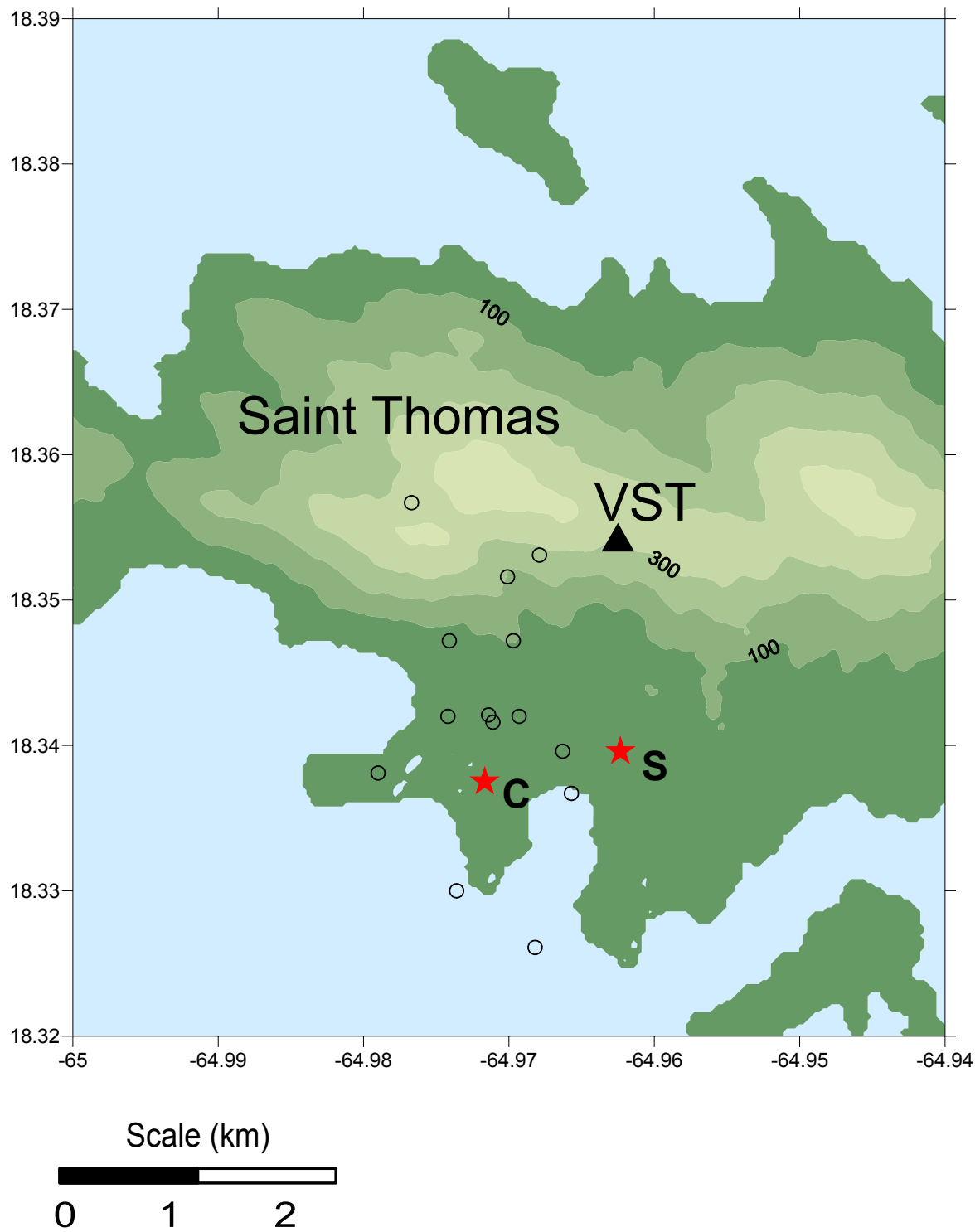
Figure 9. Artificial Seismic Sources registered by the local network in the period 1979-1980. Blasting occurred at sites C and S during that period. Events occurred Monday- Friday, and daytime (i.e.1000-2200UT). Locations are from use of *Velest* in JHD mode. Event location appear to be shifted west about 500 or less from the blast sites, and scatter north and south about 1 kilometer.